

# Large-Scale Outer Rings of Early-type Disk Galaxies

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We have searched for presence of current star formation in outer stellar rings of early-type disk (S0-Sb) galaxies by inspecting a representative sample of nearby galaxies with rings from the recent Spitzer catalog ARRAKIS (Comerón et al. 2014). We have found that regular rings (of R-type) reveal young stellar population with the age of less than 200 Myr in about half of all the cases, while in the pseudorings (open rings, R'), which inhabit only spiral galaxies, current star formation proceeds almost always.

# 1 INTRODUCTION

Large-scale stellar rings are frequent structural components of disk galaxies. Vorontsov-Velyaminov [1, 2] insisted to consider them as a part of morphology which is just so important as spiral arms or bars. Indeed, rings of various scales are present in more than a half of disk galaxies [3]. Just like spiral arms, these structures may have a smooth regular appearance or be clumpy and irregular; they may have the galaxy nucleus in the geometrical center or may be shifted relative to the galactic center [4]. All these features evidently have an evolutionary sense and are related to the origin of the ring. Now, the most popular scenarios of the origin of ring structures in galaxies are the resonance scenario and the impact one. In the former case, formation of a ring is provoked by a presence of a bar: the presence of non-axisymmetric density perturbation (and so the triaxiality of the gravitational potential), which rotates as a rigid body demonstrating an angular velocity constant along the radius of the disk, distinguishes dynamically certain radial disk zones where rotation of the bar proceeds in resonance with the nearly circular differential gas rotation. Near these Lindblad resonance radii, the cloud orbits crowd together, gas gets compressed, triggering the conditions for intense, very efficient star formation, resulting in the formation of radial enhancement in the distribution of stars, in other words, stellar rings [5, 6, 7, 8]. The manifold theory is a modification of the resonance mechanism, where the flux tubes are produced by stable gas orbits around the equilibrium points in the bar triaxial potential [9]. The impact mechanism [10, 11, 4, 12] involves an external influence: it is suggested that all very contrast rings are formed as a result of infall of a companion galaxy from a highly inclined orbit onto the disk of a galaxy, just near the center. The impact event results in the disk plane vertical oscillations and generates a ring-like density wave running outwards through the galactic disk. If the disk contains gas, intense star formation starts at a radius where the gas is compressed to the critical density, generating a ring of young stars. However, even in the case of a gas-less, purely stellar disk, the impact

effect may give rise to a transient surface density ring, expanding outwards [13]. It should be noted however that the most popular resonance mechanism affects only gas. It is because from the dynamical point of view, the gas is a collisional system lacking “elasticity” of the stellar components of the disks. Gas clouds cannot traverse the radii where chaotic orbits dominate – the resonance areas. There shock fronts develop, and the gas condenses at a given radius, then igniting star formation. As a result, the gas ring becomes a stellar ring-like structure of the disk.

The third possibility to form an outer ring-shaped structure in a galaxy, which, as will be shown below, we consider to be the most likely one, is accretion of the outer gas from a neighboring galaxy through the gravitational tides or from a cosmological filament during hierarchical assembly of the matter. This scenario is not yet very popular among the astronomical community. Once it was discussed concerning the discovery of the Hoag object [14], as the ring of this galaxy is very massive, and an absolutely round (axisymmetric?) early-type galaxy is located in its center. Neither the resonance scenario, nor the impact effect (both affecting only the own gas disk of the galaxy) would produce such an exotic configuration. However, as early as in the survey of Buta and Combes [7], it was noted that no other galaxies similar to the Hoag object were found and that almost all other outer rings were accompanied by a non-axisymmetric distortion of the isophotes in the centers of the galaxies. It has been concluded that the vast majority of the outer rings, at least those visibly residing in the main planes of symmetry of the galaxies, have the resonance origin.

The observational statistics of ring structures in galaxies was studied extensively. Ronald Buta [15, 16, 17] made a lot of effort, comparing the metric properties of rings and bars, and collected arguments in favor of the resonance scenario for the origin of the most considered rings. However, numerous cases are known of the presence of rings, sometimes two or three simultaneously, at different radii in the galaxies without bars, and often these galaxies are completely isolated, with no companions or signs of interaction that unfavored also the impact

scenario. Sil'chenko and Moiseev [18] noted that the very presence of the rings in galaxies without bars and traces of collision with another galaxy indicate that the origin of rings in galaxies can be very diverse, including also smooth gas accretion from outside. Interestingly, along the Hubble morphological sequence, the frequency of bars and that of rings drift oppositely. The morphological analysis in the near infrared (at  $2\text{--}4\ \mu\text{m}$ ) has shown that in S0 (also disk!) galaxies, the strong bars can be met much rarer than even in their nearest neighbors on the Hubble's fork, early spiral galaxies Sa–Sb ( $46 \pm 6\%$  versus  $64\text{--}93\%$  [19]), while the outer ring structures, in contrast, exist in 60% of S0 galaxies and only in 20% of Sb galaxies [3]. A large catalog of the ring-shaped structures in the disks, called ARRAKIS [3] was recently compiled based on the results of a morphological survey of nearby galaxies with the Spitzer Space Telescope at the wavelengths of  $3.6$  and  $4.5\ \mu\text{m}$  [20]. This catalog describes evidently only stellar rings, because at the wavelengths of around  $4\ \mu\text{m}$  we see the bulk of the old stellar populations. Since all the popular models relate the appearance of ring-shaped structures to the gas condensation and subsequent starburst at a certain radius, it would be interesting to check how often the stellar ring structures in galaxies reveal the signs of current star formation, especially if such star formation is not present in the rest of the disk (as it takes place in the S0 galaxies by definition). The survey of the morphology of nearby galaxies in the ultraviolet (UV) bands by the GALEX space telescope has provided necessary observational data to address this issue [21]. In the near-UV band, we see mostly the stellar population younger than a few hundred million years old. Thus, the fraction of outer stellar rings visible in the near UV gives us a rough estimate of the outer ring lifetime or of the time of their dissipation. Similar analysis has recently been done by Sebastian Comerón [22] for a sample of inner rings in the galaxies of the S4G survey. He had picked inner rings from the ARRAKIS catalog and identified them on the GALEX maps and in the narrow-band images got around the emission  $\text{H}\alpha$  line. His analysis has shown that in the early-type disk galaxies (S0–Sab) only 21% ( $\pm 3\%$ ) of the inner rings do not radiate in the UV (though in the far UV, at  $1500\ \text{\AA}$ , that reduces the

age of the stellar population searched for in this band even more). Accordingly, the dissipation time of the inner rings within the frame of hypothesis of their resonance origin appears to be at least 200 Myr, that is comparable to a single rotation period in the central part of a galaxy. In the present study we have repeat this analysis for a sample of *outer* rings in the early-type disk galaxies from the ARRAKIS catalog searching for recent star formation there.

## 2 THE SAMPLE

We have selected a sample of early-type disk galaxies, from S0 to Sb, with the outer ring-shaped structures from the ARRAKIS atlas and catalogue [3]. To classify and describe the galaxies, this atlas used the images from the Spitzer Survey of Stellar Structure in Galaxies (S4G) [23], which are in public access, and their morphological analysis from [20]. The S4G sample has the following restrictions: distance of the galaxies  $D < 40$  Mpc; galactic latitude  $|b| > 30^\circ$ ; the blue integrated magnitude corrected for dust extinction in our Galaxy, inclination of the galaxy disk plane to our line of sight, and the K-correction  $m_{B,\text{corr}} < 15.5$ ; angular diameter up to the 25th isophote in  $B > 1'$ . An outer ring-shaped feature in the ARRAKIS, just like other medium-scale features described in this catalog, was identified by inspecting the residual images of the galaxies obtained by subtracting a model image consisted of four standard components (nucleus, bulge, disk, bar) from the near-infrared galaxy images. All the S4G galaxies, more than 2000 nearby ones, were proceeded through this pipeline (S4G pipeline 4, P4). From the ARRAKIS we have selected the galaxies with the outer ring features classified as R, RL, R<sub>1</sub>, and R<sub>2</sub>-type rings. Further, this group of rings will be considered as a whole and indicated by the letter R; consequently, the pseudorings (open rings) will be marked as R'. Because of a statistically small number of selected objects, finer separation into subtypes (R, R<sub>1</sub>, R<sub>2</sub>, RL etc) has not been undertaken. The main difference between a ring and a pseudoring is a shape of the former as a closed outer feature with the surface brightness dip between the inner part of the galaxy and the ring. If in the ARRAKIS a galaxy was listed as possessing two outer

ring-shaped structures, we took into account only the outermost of the rings. Just like in the ARRAKIS, the galaxies with the outer isophote ellipticity exceeding 0.5 (edge-on disks) were not included into the sample because of large uncertainty in the classification. The S4G full sample includes 2331 galaxies of all morphological types [23], and according to the ARRAKIS, 277 of them have an outer ring-shaped feature R or R' (for 18 of them two outer ring-shaped features are noted). After the additional selection by the morphological type (202 galaxies of 277 have the S0–Sb morphological types) and by the ellipticity ( $1 - b/a$  less than 0.5), 145 galaxies were left in our sample.

Let us note that many years ago Kostyuk [24] compiled a list of 143 ring-shaped galaxies selected ‘by eye’ from the photographic copies of the Palomar Observatory Sky Survey (POSS) maps of all the northern sky. If we apply additional restrictions on the size, larger than  $1.0'$ , and on the galactic latitude,  $|b| > 30^\circ$ , in that list we are left with 51 galaxies. And only 18 galaxies from the list of [24] have Hubble velocities lower than  $3000 \text{ km s}^{-1}$ ; 11 of them are included into the ARRAKIS. We admit that the visual inspection is less effective than the pipeline reduction, however, the above mentioned list includes some very interesting galaxies not included into the ARRAKIS, a detailed study of which is planned by us in the future.

### 3 CURRENT STAR FORMATION IN THE OUTER RINGS

All the 145 galaxies of our sample have been retrieved in the data archive of the GALEX space telescope <sup>1</sup>. Rather massive, and so young, stars having lifetimes of up to 200 Myr dominate in the near-UV spectral range [25, 26]. So to study the presence of young stars, we searched for the images in the near-UV band (NUV) at 1770–2730 Å expressed as intensity maps. The results of our search have revealed that the data for nine galaxies from the list are missing in the GALEX survey, for 16 galaxies their GALEX images clearly show a spiral structure outside

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<sup>1</sup><http://galex.stsci.edu/GR6/>

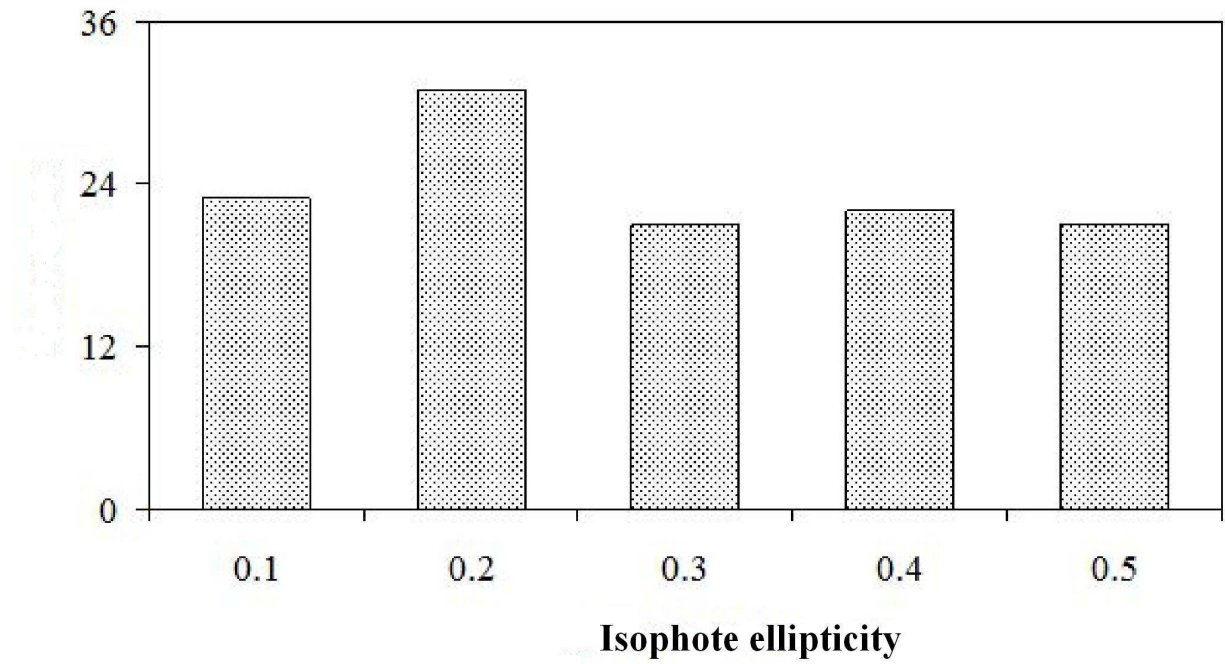


Figure 1: Distribution of the selected ring-shaped galaxies by the outer isophote ellipticity.

the outer ring, and bright stars projected near to two galaxies prevent the analysis of their faint outer UV-structures. Hence, these 18 galaxies were excluded from our analysis.

Finally, the list for studying the UV morphologies of the outer rings in the early-type disk galaxies consists of 118 galaxies. Figure 1 shows the distribution of these ring-shaped galaxies by the ellipticity of the outer isophotes according to the S4G survey data. This distribution is fairly flat, and we assure that there is no bias through the inclination of the galaxy, only after excluding the disks inclined at an angle of more than  $60^\circ$  ( $b/a > 0.5$ ). The fractions of various morphological types among the ring-possessing and pseudoring-possessing galaxies differ (Fig. 2). Among the galaxies with pseudorings,  $R'$ , there are no S0 galaxies. The galaxies with the closed R-type rings, on the contrary, are dominated by the S0 type, and the presence of the morphological type Sab–Sb is several times smaller than that in the galaxies with pseudorings  $R'$ .

We have estimated quantitatively the significance of the NUV flux in the outer rings of the galaxies by calculating the signal-to-noise ratio in the fixed area of the images accumulated by the GALEX telescope. An ellipse with the major and minor axes  $D_r$  and  $d_r$  (according to ARRAKIS) was superposed onto the NUV image of every galaxy.

Table 1: A list of early-type disk galaxies with the outer ring-shaped structures

Galaxy	Type	Ring size (ARRAKIS), arcmin	Disk size (RC3), arcmin	Ring type (ARRAKIS)	Is UV present?	$k$	Notes
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
NGC 210	SABab	$4.08 \times 2.90$	$5.01 \times 3.31$	$R'_2L$	+	8	2
NGC 254	SAB0	$1.59 \times 1.25$	$2.46 \times 1.52$	R	–	–	–
NGC 474	SAB0/a	$2.23 \times 2.07$	$7.08 \times 6.30$	$R'$	–	–	–
NGC 615	SABa	$2.26 \times 0.70$	$3.63 \times 1.45$	$R'_2$	+	4	2
NGC 691	SAab	$2.74 \times 1.93$	$3.47 \times 2.63$	R	+	3	2
NGC 718	SABa	$1.42 \times 1.09$	$2.34 \times 2.04$	$R'$	–	–	–
NGC 986	SBab	$3.52 \times 2.59$	$3.89 \times 2.96$	$R'$	+	10	1
NGC 1022	SAB0/a	$2.08 \times 1.66$	$2.40 \times 1.99$	RL	–	–	–



Table 1: (Contd.)

Galaxy	Type	Ring size (ARRAKIS), arcmin	Disk size (RC3), arcmin	Ring type (ARRAKIS)	Is UV present?	$k$	Notes
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
NGC 1068	SAa	$5.81 \times 4.89$	$7.08 \times 6.02$	R	+	2	2
NGC 1258	SABa:	$0.78 \times 0.35$	$1.35 \times 0.93$	R'	+	20	2
NGC 1291	SAB0	$8.47 \times 7.08$	$9.77 \times 8.11$	R	+	5	2
NGC 1300	SBb	$5.63 \times 4.90$	$6.17 \times 4.07$	R'	+	8	2
NGC 1326	SAB0	$2.83 \times 1.87$	$3.89 \times 2.88$	R <sub>1</sub>	+	5	2
ESO 548-23	SA0	$0.66 \times 0.35$	$1.05 \times 0.47$	RL	+	3	3
NGC 1350	SAB0/a	$5.35 \times 2.60$	$5.25 \times 2.83$	R	+	7	2
NGC 1357	SA0/a	$2.74 \times 2.20$	$2.81 \times 1.95$	R'L	—	—	—
NGC 1398	SBa	$4.64 \times 3.17$	$7.08 \times 5.38$	R	+	9	2
NGC 1433	SBa	$6.26 \times 4.48$	$6.46 \times 5.88$	R' <sub>1</sub>	+	3	1, 2
NGC 1436	SABab	$1.59 \times 0.99$	$2.95 \times 2.01$	R'	+	16	2
NGC 1452	SB0/a	$2.54 \times 1.43$	$2.24 \times 1.48$	RL	—	—	—
IC 1993	SABab	$1.47 \times 1.44$	$2.46 \times 2.14$	R'	+	14	2
NGC 1533	SB0	$1.66 \times 1.43$	$2.76 \times 2.34$	RL	+	3	3
NGC 1566	SABb	$7.55 \times 6.34$	$8.32 \times 6.57$	R' <sub>1</sub>	+	6	2
NGC 1640	SBa	$1.74 \times 1.55$	$2.63 \times 2.05$	R'	+	6	2
NGC 1808	SABa	$6.38 \times 4.62$	$6.46 \times 3.87$	R <sub>1</sub>	+	3	1, 2
NGC 2681	SAB0/a	$2.35 \times 2.13$	$3.63 \times 3.30$	R	+	3	3
NGC 2685	S0	$4.08 \times 1.80$	$4.47 \times 2.37$	R	—	—	—
NGC 2712	SABab	$2.73 \times 1.16$	$2.88 \times 1.59$	R'	+	3	2
NGC 2780	SBa	$0.67 \times 0.49$	$0.89 \times 0.66$	R'	+	8	3
NGC 2859	SAB0	$3.42 \times 2.73$	$4.26 \times 3.80$	R	+	2	—
NGC 2893	SAB0	$0.87 \times 0.69$	$1.12 \times 1.02$	RL	+	5	1, 2
NGC 2962	SAB0	$2.13 \times 1.42$	$2.63 \times 1.95$	R	+	4	2
NGC 3166	SB0	$4.11 \times 1.73$	$4.79 \times 2.35$	RL	+	2	3
NGC 3185	SABa	$2.51 \times 1.65$	$2.35 \times 1.59$	RL	—	—	—
NGC 3248	SA0	$1.77 \times 1.10$	$2.51 \times 1.56$	RL	—	—	—
NGC 3266	SB0	$0.79 \times 0.60$	$1.55 \times 1.32$	RL	—	—	—
NGC 3368	SAB0	$5.94 \times 3.57$	$7.58 \times 5.23$	RL	+	4	2
NGC 3380	SAB0/a	$1.35 \times 1.29$	$1.70 \times 1.34$	RL	+	2	1
NGC 3489	SB0	$1.53 \times 0.45$	$3.55 \times 2.02$	R	+	8	2
NGC 3504	SABa	$2.03 \times 1.89$	$2.69 \times 2.10$	R' <sub>1</sub>	+	6	2

Table 1: (Contd.)

Galaxy	Type	Ring size (ARRAKIS), arcmin	Disk size (RC3), arcmin	Ring type (ARRAKIS)	Is UV present?	$k$	Notes
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
NGC 3507	SABb	$2.34 \times 2.11$	$3.39 \times 2.88$	R'	+	8	2
NGC 3583	SABab	$1.96 \times 1.04$	$2.81 \times 1.83$	R'	+	13	2
NGC 3637	SB0	$1.44 \times 1.12$	$1.59 \times 1.55$	RL	—	—	—
NGC 3675	SAb	$2.42 \times 0.89$	$5.89 \times 3.12$	R'	+	10	2
IC 2764	SA0	$0.84 \times 0.70$	$1.62 \times 1.41$	R	+	6	2
NGC 3687	SABab	$1.43 \times 1.34$	$1.91 \times 1.91$	RL	+	6	2
NGC 3786	SA0/a	$1.77 \times 0.79$	$2.19 \times 1.29$	R	—	—	—
NGC 3892	SAB0	$2.55 \times 2.20$	$2.95 \times 2.24$	RL	—	—	—
NGC 3941	SB0	$1.78 \times 0.94$	$3.47 \times 2.29$	R	+	3	3
NGC 4045	SABab	$1.91 \times 0.95$	$2.69 \times 1.86$	R' <sub>1</sub> L	+	4	2
NGC 4050	SABa	$3.36 \times 2.01$	$3.09 \times 2.10$	RL	—	—	—
NGC 4102	SABab	$1.24 \times 0.67$	$3.02 \times 1.72$	R'	+	20	2
IC 3102	SAB0/a	$2.76 \times 1.45$	$2.57 \times 1.36$	R'L	—	—	—
NGC 4245	SB0	$2.65 \times 1.89$	$2.88 \times 2.19$	RL	—	—	—
NGC 4286	SA0	$0.78 \times 0.55$	$1.59 \times 1.00$	RL	+	4	3
NGC 4314	SBa	$3.72 \times 3.03$	$4.17 \times 3.71$	R' <sub>1</sub>	—	—	—
NGC 4355	SAB0/a	$0.97 \times 0.49$	$1.45 \times 0.71$	R'L	+	2	3
NGC 4369	SB0/a	$1.42 \times 1.30$	$2.09 \times 2.05$	R	+	2	3
NGC 4378	SAa	$2.93 \times 2.45$	$2.88 \times 2.68$	R'	+	3	2, 3
NGC 4380	SAab	$2.02 \times 1.07$	$3.47 \times 1.91$	R	+	7	2, 3
NGC 4394	SB0/a	$2.74 \times 2.45$	$3.63 \times 3.23$	R	+	9	2
NGC 4405	SABa	$1.05 \times 0.66$	$1.78 \times 1.16$	R	+	3	3
NGC 4407	SBab	$2.81 \times 1.52$	$2.35 \times 1.52$	R'L	—	—	—
NGC 4424	SB0/a	$3.18 \times 1.53$	$3.63 \times 1.82$	R' <sub>2</sub> L	—	—	—
NGC 4450	SABa	$3.43 \times 2.20$	$5.25 \times 3.88$	R'	+	3	2
NGC 4454	SAB0/a	$2.00 \times 1.83$	$2.00 \times 1.70$	RL	—	—	—
NGC 4457	SAB0	$4.04 \times 3.76$	$2.69 \times 2.29$	R	—	—	—
NGC 4579	SBa	$4.33 \times 3.10$	$5.89 \times 4.65$	RL	—	—	—
NGC 4580	SAa	$1.86 \times 1.26$	$2.09 \times 1.63$	R'	—	—	—
NGC 4593	SBa	$3.54 \times 2.51$	$3.89 \times 2.88$	R'	+	4	2
NGC 4596	SB0/a	$3.40 \times 2.66$	$3.98 \times 2.95$	RL	—	—	—
NGC 4639	SBab	$2.36 \times 1.38$	$2.76 \times 1.87$	R'	+	7	2

Table 1: (Contd.)

Galaxy	Type	Ring size (ARRAKIS), arcmin	Disk size (RC3), arcmin	Ring type (ARRAKIS)	Is UV present?	$k$	Notes
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
NGC 4659	SAB0	$1.04 \times 0.64$	$1.74 \times 1.25$	R	+	2	3
NGC 4691	S0/a	$2.79 \times 2.15$	$2.81 \times 2.28$	R'L	—	—	—
NGC 4698	SA0/a	$7.91 \times 2.73$	$3.98 \times 2.47$	R	+	2	—
NGC 4699	SB0/a	$1.95 \times 1.48$	$3.80 \times 2.62$	R'	+	7	2
NGC 4736	SABa	$10.58 \times 8.68$	$11.22 \times 9.09$	R	+	2	—
NGC 4750	SAa	$1.52 \times 1.33$	$2.04 \times 1.86$	R'	+	18	2
NGC 4772	SA0/a	$3.85 \times 1.93$	$3.38 \times 1.69$	R'	—	—	—
NGC 4795	SBa	$1.38 \times 1.13$	$1.86 \times 1.58$	R'	—	—	—
NGC 4800	SAa	$1.22 \times 0.97$	$1.58 \times 1.17$	R'	+	8	3
NGC 4826	SAa	$7.17 \times 3.10$	$10.00 \times 5.40$	R'	+	2	3
NGC 4856	SB0	$2.44 \times 0.65$	$4.26 \times 1.19$	RL	—	—	—
NGC 4880	SAB0	$2.05 \times 1.48$	$3.16 \times 2.47$	RL	—	—	—
NGC 4941	SA0/a	$3.33 \times 2.36$	$3.63 \times 1.96$	RL	+	2	1, 2
NGC 4984	SAB0/a	$5.07 \times 2.82$	$2.76 \times 2.18$	R'	—	—	—
IC 863	SBb	$0.51 \times 0.30$	$1.82 \times 1.20$	R'	+	4	3
IC 4214	SAB0/a	$2.03 \times 1.25$	$2.24 \times 1.28$	R <sub>1</sub>	+	3	2
NGC 5101	SB0/a	$5.31 \times 4.61$	$5.37 \times 4.56$	R' <sub>2</sub>	+	2	2
NGC 5134	SAB0/a	$3.53 \times 2.99$	$2.76 \times 1.65$	R	—	—	—
NGC 5375	SBa	$2.24 \times 1.82$	$3.24 \times 2.75$	R'	+	4	2
NGC 5377	SAB0/a	$4.05 \times 2.03$	$3.72 \times 2.08$	R <sub>1</sub>	+	2	2
NGC 5534	SBa	$1.21 \times 0.83$	$1.41 \times 0.83$	R'L	+	6	2
NGC 5602	SA0	$1.05 \times 0.54$	$1.45 \times 0.77$	RL	—	—	—
NGC 5678	SAb	$2.31 \times 1.17$	$3.31 \times 1.62$	R'	+	6	2
NGC 5701	SB0/a	$3.21 \times 2.72$	$4.27 \times 4.05$	R' <sub>1</sub>	+	9	2
NGC 5713	SBab:	$1.67 \times 1.48$	$2.76 \times 2.45$	R'	+	2	3
NGC 5728	SB0/a	$3.61 \times 2.34$	$3.09 \times 1.76$	R <sub>1</sub>	—	—	—
NGC 5750	SAB0/a	$2.70 \times 1.30$	$3.02 \times 1.60$	RL	—	—	—
NGC 5757	SBab	$1.35 \times 1.19$	$2.00 \times 1.62$	R' <sub>2</sub>	+	3	2
NGC 5806	SABab	$2.68 \times 1.46$	$3.09 \times 1.58$	R'	+	2	2
NGC 5850	SBab	$4.00 \times 3.31$	$4.27 \times 3.71$	R'	+	2	2
NGC 5957	SBa	$2.38 \times 2.08$	$2.82 \times 2.62$	R'	+	3	2
NGC 6012	SBab	$2.57 \times 2.32$	$2.09 \times 1.50$	R'	+	4	2

Table 1: (Contd.)

Galaxy	Type	Ring size (ARRAKIS), arcmin	Disk size (RC3), arcmin	Ring type (ARRAKIS)	Is UV present?	$k$	Notes
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
NGC 6217	SBb	$2.72 \times 2.46$	$3.02 \times 2.51$	R'	+	3	1
NGC 6340	SA0/a	$1.80 \times 1.52$	$3.24 \times 2.94$	R	+	2	–
NGC 7051	SABb	$1.12 \times 0.97$	$1.32 \times 1.09$	R' <sub>2</sub>	+	2	1
NGC 7098	SAB0/a	$3.63 \times 2.26$	$4.07 \times 2.65$	R	+	3	2
NGC 7140	SABab	$3.72 \times 2.60$	$4.17 \times 3.00$	R'	+	2	2
NGC 7191	SABb	$0.83 \times 0.37$	$1.59 \times 0.55$	R'	+	8	2
NGC 7219	SABa	$1.36 \times 0.83$	$1.74 \times 1.04$	R' <sub>2</sub>	+	10	2
IC 1438	SAB0/a	$1.77 \times 1.32$	$2.40 \times 2.04$	R <sub>1</sub>	+	3	2
NGC 7421	SABab	$1.68 \times 1.54$	$2.04 \times 1.82$	R'	+	6	2
IC 5267	SA0/a	$4.65 \times 3.31$	$5.25 \times 3.88$	RL	+	3	2
NGC 7479	SBb	$2.77 \times 2.13$	$4.07 \times 3.10$	R'	+	20	2
NGC 7552	SBa	$3.08 \times 2.52$	$3.39 \times 2.68$	R' <sub>1</sub>	+	10	2
NGC 7724	SABa	$0.88 \times 0.54$	$1.45 \times 1.00$	R'	+	5	2
NGC 7731	SABa	$1.09 \times 0.85$	$1.41 \times 1.12$	R' <sub>2</sub>	+	2	2

The outer rings are generally faint features of galaxies. The galaxies in which an external, with respect to the ring, extension of the structureless disk is visible in the NUV band were not excluded from our sample. To estimate a brightness of the ring in the NUV band, the GALEX image of every galaxy was smoothed by a 5–10-pixel window. If the mean count value per pixel in the ring area exceeded two values of the surrounding sky background, then the galaxy was marked as having NUV radiation in its outer ring-shaped feature.

Our estimates of the sky background in the GALEX intensity maps over vicinity of 117 galaxies of the list above give an average value of  $0.00274 \text{ cts s}^{-1}$  per pixel, which corresponds to the average sky surface brightness of  $27.36^{\text{m}}/\square''$  in the NUV band in the AB system. The sky background around galaxies varies in the range of  $0.0020\text{--}0.0042 \text{ cts s}^{-1}$ , with the standard deviation of  $0.00049 \text{ cts s}^{-1}$ . One galaxy (NGC 1068) was prominent as concerning its sky NUV background and was not included into the background estimation sample, since only for this

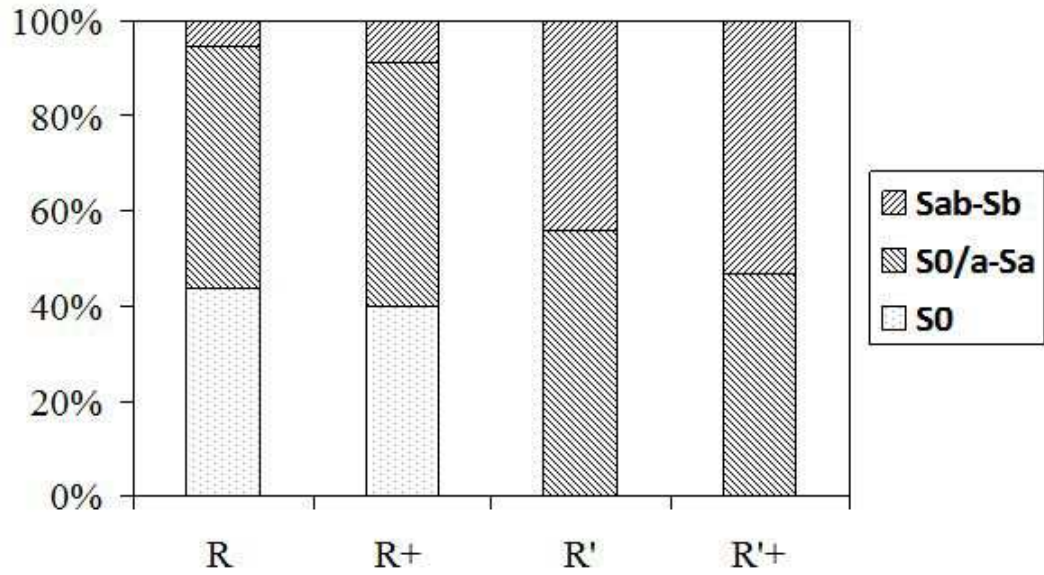


Figure 2: Fraction of galaxies of different morphological types (S0, S0/a-Sa, Sab-Sb) among the ring-shaped galaxies. By the big ‘R’ the galaxies with closed rings are marked, R+ are the ring galaxies with the NUV radiation in the ring, R’ are the pseudoring galaxies, R’+ are the pseudoring galaxies with UV radiation in the ring.

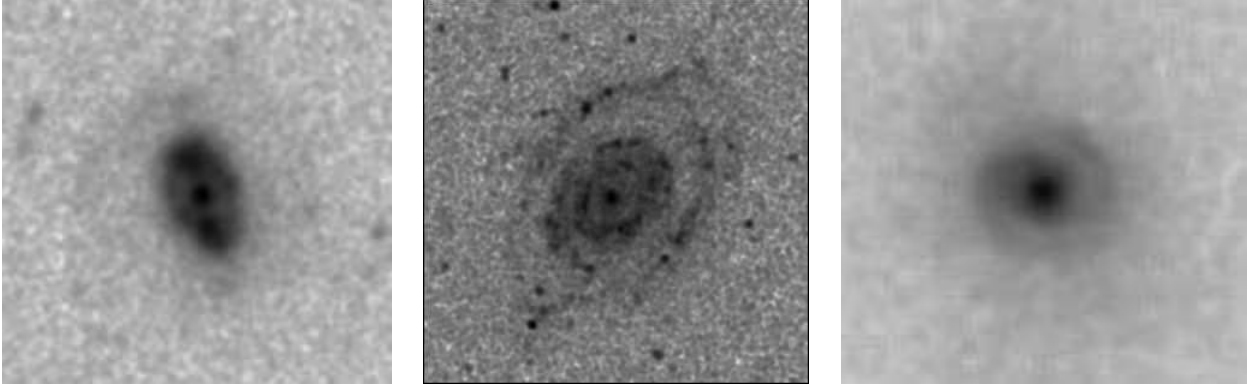


Figure 3: Examples of the GALEX NUV-images for the galaxies with the ring structures (type R), which correspond to the different ring subtypes given in the last column of the Table 1. The left plot: the ring subtype 1, unclosed (NGC 3380, the field-of-view size is  $2.5'$ ); the central plot: the ring subtype 2, clumpy (IC 5267, the field-of-view size is  $8'$ ); the right plot: the ring subtype 3, a filled disk (NGC 2681, the field-of-view size is  $2'$ ).

galaxy the value of the sky background is  $0.0070 \text{ ctss}^{-1}$ . For 36 galaxies from the list with faint (maximum three values of sky background) ring-shaped features the average background is  $0.00278 \text{ ctss}^{-1}$  per pixel falling into the same range of values and standard deviations, as indicated above for the whole sample. This corresponds to the sky surface brightness in the NUV band of  $27.35^{\text{m}}/\square''$ .

The list consisting of 118 galaxies with the outer ring-shaped structures which we have studied is presented in Table 1. The table contains in its columns as follows: the name of the galaxy; the galaxy classification taken by us from ARRAKIS without details; major and minor axes of the outer ring-shaped structure  $D_r$  and  $d_r$  in arcminutes (from ARRAKIS); the major  $2a$  and minor  $2b$  axes of isophotes of the galactic disk at the surface brightness level of  $25^{\text{m}}/\square''$  in the blue  $B$ -band (from the RC3 catalog [27]); the type of the ring-shaped structure from ARRAKIS; the presence or absence of a ring-shaped UV signal in the NUV band according to the GALEX (marked with “+” or “−” respectively); the  $k$  coefficient – an approximate average value of the UV flux in the ring per pixel in the units of the sky background according to the

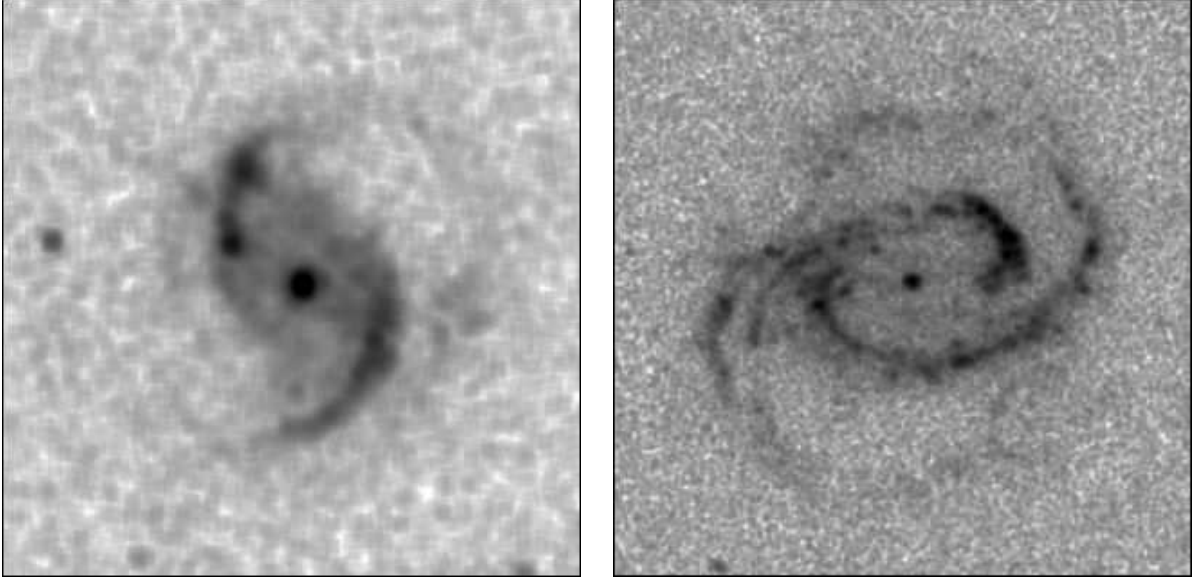


Figure 4: Examples of the GALEX images, in the NUV band, for the galaxies with pseudoring structures ( $R'$ ), which correspond to different types marked in the last column of Table 1. The left plot: the ring subtype 1, unclosed (NGC 986, the field-of-view size is  $5'$ ); the right plot: the ring subtype 2, clumpy (NGC 1300, the field-of-view size is  $8'$ ).

GALEX (if  $k < 2$ , the minus is in this column); the notes to the shape of the ring structure as seen in the NUV: 1—incomplete, 2—clumpy, 3—a filled disk. Thus, a galaxy without the notes and with the “+”-sign in the column 6 has indeed a rather uniform ring-shaped structure in the UV, visible at all azimuths. Figures 3 and 4 show the examples of all the kinds of ring-shaped structures described in the notes of Table 1.

Table 2 summarizes the statistics of ring-shaped galaxies from the list dividing by the morphological type and by the presence or absence of the UV radiation in the ring. Our list includes only 24 galaxies without bars (SA type, see the second column of Table 1) and 94 barred galaxies (of SB and SAB types). Although according to Table 2 the number of galaxies with bars and rings is four times larger than the galaxies with rings but without bars, we note that the presence of a bar in the galaxy does not affect how often the UV radiation is detected

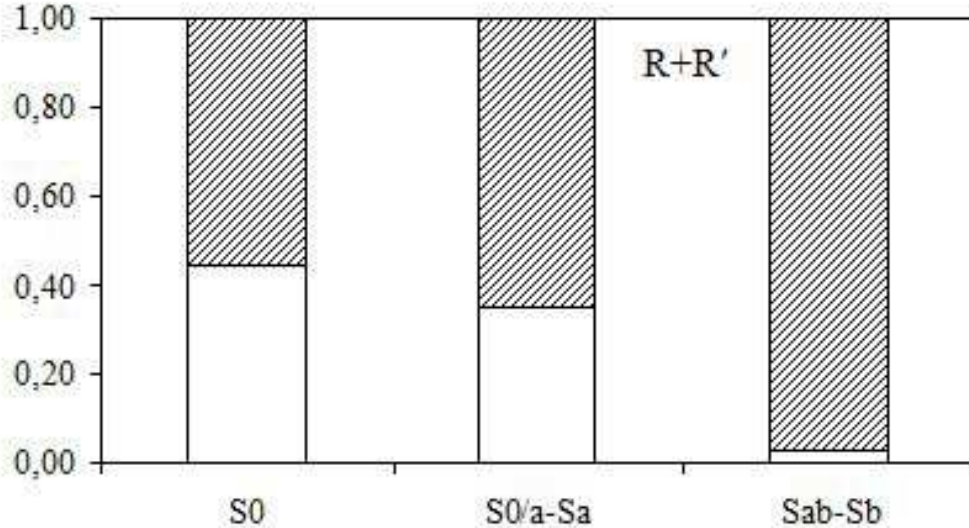


Figure 5: Fraction of galaxies with ultraviolet radiation in the ring (shaded) for different morphological types of all ring, R+R', galaxies. The total number of R+R' galaxies in each morphological type is normalized to unity.

in the ring of a galaxy, i.e., how often the current star formation proceeds in the rings. So in the following discussion, we do not make a separation between the galaxies with and without a bar.

Figures 5–7 present the histograms at which the fractions of the galaxies with UV radiation in the ring (the shaded portion of the column) among all R+R' ring-shaped galaxies are presented, and also those are shown separately for the ring R and pseudoring R' galaxies dividing according to their morphological types. All types of ring-shaped structures are characterized by an increase in this fraction along the Hubble fork, from S0 to Sb galaxies. But even at the minimum, for the S0 galaxies, it stays at 56%, which is about a half of all rings. Almost



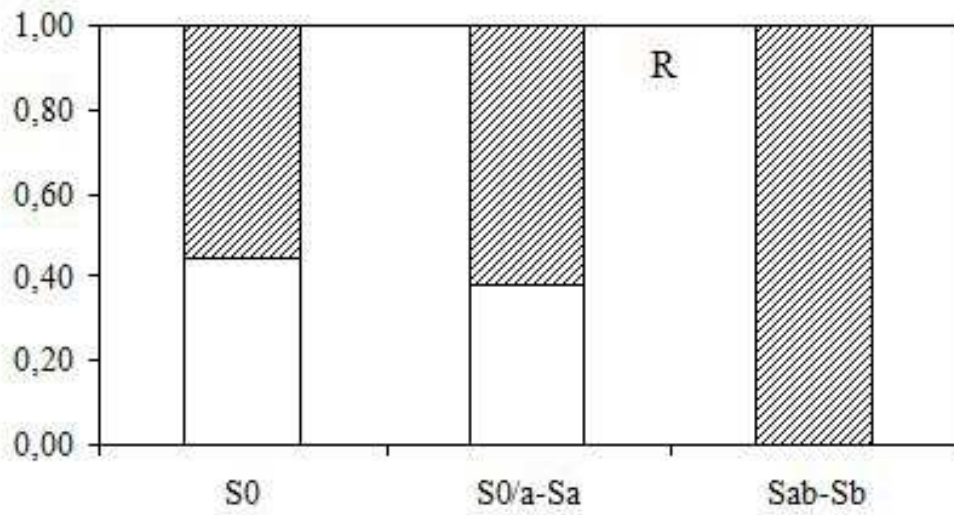


Figure 6: Fraction of galaxies with ultraviolet radiation in the ring (shaded) for different morphological types among the R galaxies. The total number of galaxies in each morphological type is normalized to unity.

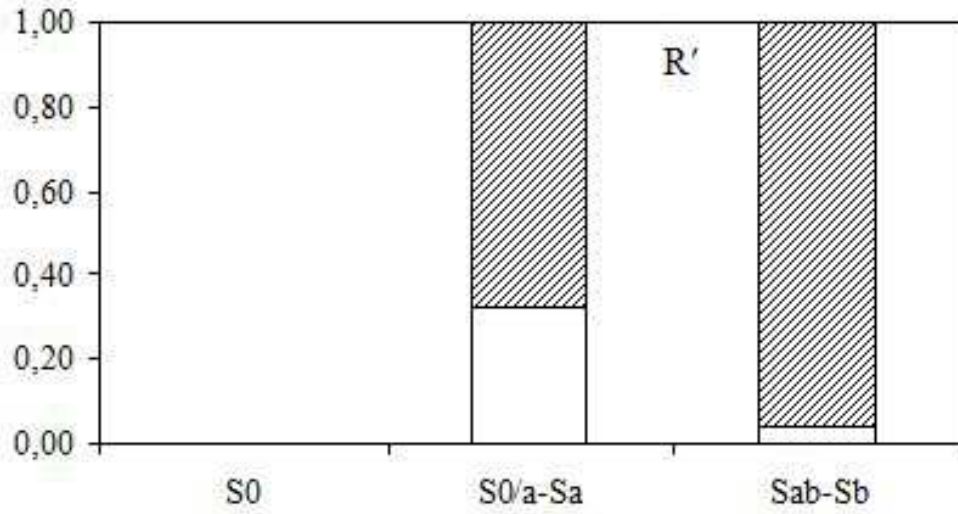


Figure 7: Fraction of galaxies with ultraviolet radiation in the ring (shaded) for different morphological types among the pseudoring ( $R'$ ) galaxies. The total number of  $R'$  galaxies in each morphological type is normalized to unity. The S0 galaxies never possess pseudorings.

all the spiral Sab–Sb galaxies (29 of 30) possess UV radiation in their ring-shaped feature.

The average ratio of the major axis of the ring  $D_r$  (the third column of Table 1) to the major axis of the outer isophote of the galactic disk according to the RC3 data (the fourth column of Table 1) is 0.81 with a dispersion of about 0.25. Seventy percent of the galaxies in the list fall within the ratio interval of 0.6–1.0. Among the galaxies with the UV radiation in the ring-shaped structures (84 galaxies), the subtype 2, which marks a clumpy structure (see the eighth column of Table 1), is the most frequent – 61 galaxies. Interestingly, this is true for all the morphological types of the galaxies. The mean value of the  $k$  coefficient (the seventh column in Table 1) is near 6, and it increases generally from S0 to Sb. Among the ultraviolet-ring subtypes, mentioned in the eighth column of Table 1, clumpy rings, subtype 2, have the mean  $k$  coefficient almost two times larger than the other subtypes.

## 4 DISCUSSION

We have investigated the frequency of ongoing star formation in the outer stellar rings of nearby early-type disk galaxies by inspecting a representative sample (more than 100 objects) taken from the ARRAKIS catalog [3] compiling a list of galaxies with the rings seen at 4  $\mu\text{m}$ . We have found that the regular outer stellar rings of the S0 galaxies contain young stars in about half the cases, while the pseudorings of spiral galaxies contain them almost always.

Although by definition of their morphological type lenticular galaxies are thought to be devoid of large-scale star formation in the disks, in fact, at a closer look, is not exactly so. In 21% of all S0 galaxies the ultraviolet space telescope GALEX observes an extended signal, that indicates extended regions of current star formation [28]. The distribution of this extended star formation is quite curious. Recently, Salim et al. [28] examined a sample of early-type galaxies known to have ultraviolet excess. After observing them at the Hubble Space Telescope and constructing well-resolved UV images, the kind of morphology of the UV images was found to be related with the galaxy morphological type: in six ellipticals star formation is concentrated

Table 2: Distribution of ring galaxies by the type of the ring-shaped feature (R are rings, R' are pseudorings) and the galaxy morphological type

Type	All			Among them, those having “+” in the UV column					
	R + R'	R	R'	R + R'		R		R'	
S0	25	25	0	14	(56% $\pm$ 10%)	14	(56% $\pm$ 10%)	0	
of them, SB	19	19	0	11	(58% $\pm$ 11%)	11	(58% $\pm$ 11%)	0	
of them, SA	6	6	0	3	(50% $\pm$ 20%)	3	(50% $\pm$ 20%)	0	
S0/a-Sa	63	29	34	41	(65% $\pm$ 6%)	18	(62% $\pm$ 9%)	23	(68% $\pm$ 8%)
of them, SB	49	23	26	32	(65% $\pm$ 7%)	13	(56% $\pm$ 10%)	19	(73% $\pm$ 9%)
of them, SA	14	6	8	9	(64% $\pm$ 13%)	5	(83% $\pm$ 15%)	4	(50% $\pm$ 18%)
Sab-Sb	30	3	27	29	(97% $\pm$ 3%)	3	(100%)	26	(96% $\pm$ 4%)
of them, SB	26	1	25	25	(96% $\pm$ 4%)	1	(100%)	24	(96% $\pm$ 4%)
of them, SA	4	2	2	4	(100%)	2	(100%)	2	(100%)
All	118	57	61	84	(71% $\pm$ 4%)	35	(61% $\pm$ 6%)	49	(80% $\pm$ 5%)
of them, SB	94	43	51	68	(72% $\pm$ 5%)	25	(58% $\pm$ 6%)	43	(84% $\pm$ 5%)
of them, SA	24	14	10	16	(67% $\pm$ 10%)	10	(71% $\pm$ 12%)	6	(60% $\pm$ 16%)

in a small (unresolved) area, whereas in 15 of 17 S0 galaxies extended star formation was noticed, and in all 15 cases, the star formation morphology is ring-like. The rings may be of various sizes: for the narrow rings of star formation, the authors of [28] obtained a mean radius of 6.5 kpc, for the wide rings—16–20 kpc. There still exists a rare morphological subtype of ‘a disk with a hole’; however, these are actually rings with large outer radii. Among the S0 and Sa early-type disk galaxies possessing rings of star formation in the sample [28], there are equal numbers of galaxies with and without bars (8 and 11 objects respectively), so the resonance nature of the most of these rings is not quite obvious. We would like to note that the conclusion about the dominance of the ring-like morphologies as concerning the distribution of starforming regions in lenticular galaxies has already been reported earlier. As early as in 1993, during deep searching for H $\alpha$  emission in the disks of lenticular galaxies rich in neutral hydrogen, Pogge and Eskridge [29] found that star formation could be detected in half the cases, and that it was always organized as rings. It was a surprise to find that the presence or absence of star formation was not related to the amount of fuel for star formation (to the amount of

neutral hydrogen). Pogge and Eskridge [29] concluded then that star formation in S0s was probably triggered by some external kinematical factor, quite different from the gravitational instabilities, controlling star formation in thin large-scale disks of late-type spiral galaxies. Some claims about finding star formation in outer rings, where the gaseous component should in theory be stable against the processes of fragmentation, came from the detailed study of the outer neutral-hydrogen rings in early-type spiral galaxies by [30]. The most natural additional mechanism which may provoke star formation ignition in the gaseous disks with the *mean* surface density under the Kennicutt threshold [31] seems to involve shock waves. This leads us to the suggestion of the cold gas accretion from outside, perhaps from satellites on inclined orbits (to provide a compression shock wave in the main galactic disk due to vertical impact) as the dominant mechanism to form regular outer rings of star formation in the disks of early-type galaxies, where surface density of the gas, as known (see, for example [32, 33]), is significantly smaller than that in the disks of late-type galaxies, and moreover, as a rule is insufficient to support star formation on its own. At the same time, the distribution of neutral hydrogen in early-type galaxies (where the neutral hydrogen is found) is much more extended than that in spiral galaxies: regular HI structures in S0s can reach up to 200 kpc in diameter [34]. Basing on multi-colour surface photometry, Afanasiev and Kostyuk [35] have shown that the ring-shaped galaxies from the list of [24] belong mostly to the early morphological types, in agreement with the conclusions of Comerón et al. [3]. However, in [35] it was also noticed that the galaxies with outer rings have in average more extended stellar disks than the galaxies without rings. It is a strong indication on the further build-up of the outer parts of the disks through stimulated star formation in the outer rings as a result of cold gas accretion from outside.

It seems possible that the outer pseudorings of early-type spiral galaxies, where star formation proceeds in almost 100% of the cases, have the same genesis as the phenomenon of the so-called XUV disks (eXtended UltraViolet disks [36, 37]), observed in approximately 20–30% of all disk galaxies, from early to late types, in the nearby Universe. Broken (unclosed)

pseudorings may well be tightly wound spiral density waves, spreading outward into extended gas disks from the inner regions of the galactic disks. These generate also shock waves capable to stimulate star formation in diffuse gaseous medium [38, 39]. However, the origin of the XUV disks, which can be equally often found both in low-luminosity starforming galaxies and in massive galaxies that inhabit the “red sequence” and “green valley” [40], is presently also attributed to recent events of outer cold gas accretion [37, 41, 42]. Hence, for pseudorings also, the external origin through the accretion of cold gas with a high angular momentum onto the periphery of a galactic disk remains to be the most attractive. Perhaps for these structures we would prefer a slow, smooth accretion close to the galactic disk symmetry plane.

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